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The effect of furniture and floor covering upon dynamic thermal building simulations

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Abstract

In this paper, the impact of modelling furniture and floor covering in thermal building simulations is analysed and a distinct effect upon the simulated room temperatures under dynamic temperature control conditions is found. For the thermal steady state, the impact is negligible and for short-time temperature reductions, as know from night temperature set-back, the found differences are also not significant. However, if a room is dynamically heated, for example while charging its thermal mass as a measure of load shifting, distinct temperature differences between empty and furnished rooms are detected. After just 4 hours of increased set temperature, an empty massive room was 1.2 K warmer than the same modelled room with laminate flooring and furniture inside. If such simulation results are used to control load shifting activities, the system's scope of operation which is already restricted through the narrow comfort range of residents, could be yet further reduced.

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Keywords: building modelling; furniture & floor cover modelling; energy storage; thermal mass; radiative heating; dynamic heating control;

Nomenclature

d	layer thickness [m]	E	empty room
ρ	density [kg/ m³]	F	room with furniture
λ	thermal conductivity [W/ (m · K)]	C	room with carpet
c	specific thermal capacity [J/ (kg · K)]	C&F	room with furniture and carpet
ε	emissivity	$\Delta(i \leftrightarrow j)$	time/temperature difference between i and j
M	room of massive construction	V	volume [m³]
L	room of light construction	A/V	furniture exterior surface to V ratio [m² / m³]

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1. Introduction

There is a common intention to replace fossil energies as a source by renewable energies wherever possible. Among others, the energy demand of residential buildings, which accounts for about 30 % of final energy consumption in Europe [1], could play a major role supporting the usage of renewable energies. That is, firstly, because a growing extent of the buildings' energy demand can be covered locally by solar power and, secondly, because the mostly required thermal energy can be stored efficiently, thus decoupling availability of renewable energies and energy demand of the building [2]. Such demand side management (DSM) allows the building to maximize self-consumption of its own solar energy generation and potentially also cost-efficient incorporation of excess electricity from centralized wind or photo-voltaic (PV) farms. There are already some approaches presented in literature describing concepts and showing the potentials of thermal DSM with buildings [3-6]. However, such approach raises a challenge for dynamic storage mechanisms. Often, large water tanks or batteries are used but this potentially contradicts the original aim of reducing the costs of the energy system through DSM. Therefore, as an alternative, storing energy in the buildings' inherent thermal mass has been suggested [7, 8]. With this aim, temperature in different building zones should be increased when renewable energy is available in excess and inhabitants are not present. However, the temperature has to be kept in comfortable limits whenever the house is occupied. To maximize the potential of this concept in the design as well as in the operation phase, the thermal performance of actual buildings has to be predicted as accurately as possible. Since this happens mostly through dynamic thermal simulations, models that are precise, simple to use and fast to simulate are needed.

Mostly, the building envelope as well as the internal walls and floors are regarded as the building's thermal mass. But in the majority of cases the rooms are modelled as empty, e.g. furniture and floor covering are not included. However, since electricity supplied heating systems as heat pumps (HP) use low heating temperatures and radiative heating systems to increase their efficiency, the large surface area of furniture could have a noticeable effect. Also, the insulating properties of any floor covering can impact the energy transfer from the floor heating. While both the insulating impact of floorings and radiative energy exchange with furniture might have less impact in a thermal steady state, they gain importance when the heating system and therefore also the room temperatures are controlled dynamically.

Previously, on one hand, it has been experimentally shown that furniture makes a difference for floor heating and other radiative systems. Existence of furniture in the room can reduce the floor heating performance by up to 30 %, as one experiment showed [9]. This finding was also supported by numerical studies by the same group. In an analytical solution, a view factor approach has been implemented where the reduction of the surface areas involved in the room's radiative heat exchange virtually represents the furniture [10]. That research, on the other hand, found that there was only a 1-2 % impact on the cooling load when varying the view factor value between 0.3 and 0.7. In another research, only a small difference between measurements in a furnished room and calculations for an empty room is found [11]. However, in most cases the radiation exchange of furniture itself has been completely neglected and the research is only focusing on the reduction of active radiative surfaces due to the furniture. The influence of floor covering, e.g. laminate floor or carpet, has been proven by a very detailed steady state calculation. The cover material and thickness of the floor heating panel are the main influencing parameters for its performance, shows the numerical study based on finite element method [12].

All mentioned previous research has analysed the impact of floor covering and furniture only under constant thermal conditions, thus with fixed set temperatures for the building. Therefore, in this paper the impact of furniture and flooring upon the thermal conditions within a building under dynamic heating control is analysed. Since the computation time of such dynamic simulations is crucial e.g. for the inclusion in constantly recalculating model-predictive controllers, a model based on the physical representation of building materials is used instead of computationally very expensive fluid dynamics or finite element approaches.

2. Approach

2.1. Room models

The modelled room in this analysis has a floor space of 4 x 4 meter and a room height of 3 meters. The room has two exterior walls, each with a window area of 1 x 3 meters, and two interior ones. The interior walls as well as floor and ceiling are all assumed to be adjacent to other similarly conditioned rooms and are thus adiabatic. Ventilation is not taken into account, however, an infiltration air exchange is considered to be 0.18 h^{-1}.

The room is modelled according to the German EnEV 2009 [13] building standard, which represents very well insulated buildings with a typical heating energy demand in the range of $40 - 70\,\mathrm{kWh/(m^2 \cdot a)}$. However, this standard only defines the required insulation levels for all building parts in general and does not give any material properties. Since it is evident that the construction materials of walls, floor, and ceiling play the most important role in the dynamic energy storing potential, two construction variations are analysed to better distinguish the potential effects of flooring and furnishing from the effects of the building materials itself. Both a massive (M) and light (L) building construction applicable to the EnEV 2009 standard were modelled and simulated to take this influence into account. The detailed construction material data are shown in Table 1, emission coefficients are all set to 0.95. For both the massive and the light construction standards, four room models are built: an empty room (from now on noted with E), a room with floor covering only (C), a room with only furniture (F), and one with both floor covering and furniture (C&F). The room and furniture models are built in Modelica/ Dymola with all means of heat transfer considered. The convective heat transfer is modelled according to ASHRAE Fundamentals [14]. The 2-star model was used for radiative heat transfer [15]. The conductive heat transfer coefficients are assumed to be temperature-independent. For the room models with furnishing, one internal wall is assumed to be 50 % covered by furniture and thus no thermal heat transfer is taken into account there.

Table 1. Description of the modelled construction materials

Material	Layer I	Layer II	Layer III	Layer IV
	d; ρ; λ; c	d; ρ; λ; c	d; ρ; λ; c	d; ρ; λ; c
Floor M & L	0.06; 140; 0.04; 1000	0.25; 2300; 2.3; 1000	0.04; 120; 0.035; 1030	0.06; 2000; 1.4; 1000
Ceiling M	0.04; 210; 0.062; 1509	0.16; 93; 0.71; 1593	0.0275; 1018.2; 0.346; 1000	n.a.
Ceiling L	0.02; 120; 0.045; 1030	0.16; 2300; 2.3; 1000	0.015; 1200; 0.51; 1000	n.a.
Ext. wall M	0.05; 1800; 1.0; 1000	0.1; 120; 0.035; 1030	0.24; 1000; 0.5; 1000	0.015; 1200; 0.51; 1000
Ext. wall L	0.03; 1800; 1.0; 1000	0.02; 300; 0.1; 1700	0.18; 172; 0.056; 1337	0.0275; 1018.2; 0.346; 1000
Int. wall load M	0.0875; 1000; 0.5; 1000	0.015; 1200; 0.51; 1000	n.a.	n.a.
Int. wall M	0.0575; 1000; 0.5; 1000	0.015; 1200; 0.51; 1000	n.a.	n.a.
Int. wall load L	0.09; 93; 0.78; 1593	0.0275; 1018.2; 0.346; 1000	n.a.	n.a.
Int. wall L	0.05; 93; 0.44; 1593	0.0275; 1018.2; 0.346; 1000	n.a.	n.a.

2.2. Furniture and flooring models

Measurements on scaled models have been previously applied for investigating the effect of furniture; research for the effect of flooring has been carried out with detailed finite element models. This shows that including furnishing models in building simulation is definitely not trivial. However, it becomes especially challenging when using simpler fast calculating models as the midway between measurements on scaled models and highly complex computational models. Some authors suggest that virtual internal heat capacity could be used to model furniture [16]. In our paper, furniture is modelled as horizontal boards of wood or metal. The floor covering model is one capacity bordered by the virtual floor heating model on the bottom side and the room space on the top side. The furniture and flooring parameters are presented in Table 2. Data from several different sources was combined to set these parameters reasonably [17-21].

Table 2. Material properties of modelled furniture and flooring

	ρ	c	λ	ε	A/V	V
Furniture (wooden)	650	1900	0.14	0.85	105	1
Furniture (metal)	6000	500	80	0.5	200	0.05
Flooring (wood & insulation laminate)	500	1500	0.07	0.85	n.a.	0.112 (d=7 mm)

2.3. Performed analysis

Floor heating was included as a heat flow input within the floor, calculated by a PID controller for given set temperatures, and with a defined maximum heat flow of 100 W/ m^2 resulting in a total maximum heating power of 1600 W for the whole room. To analyse the effect of furniture and flooring upon the simulation quality, some measures of performance are required. The choice of analysed simulation outputs in this paper includes resulting room temperatures during and after the set temperature steps up or down. Furthermore, we analysed the time required for reaching given temperatures while heating and cooling the building.

Before any analysis, the PID controller was used to get stable conditions by simulating 10 days prior to the analysed period. For set temperature steps this period was simulated with the constant indoor air set temperature of 21 °C. For the periodic set temperature case these 10 days were simulated with the defined periodic profile. Ambient temperature is set to 0 °C at all times describing Central-Europe winter conditions.

Set temperature step up: From the steady state of 21 °C the room is heated with a set temperature of 26 °C, thus with the heating system on full power. The required time to reach the set temperature is marked. To see the actual dynamics of short term changes in heating operation, we also observe the temperature after 4 hours of heating.
Periodic step up: For this case, the set temperature of 26 °C is fixed for 4 hours and repeated periodically every 24 hours. On all other times, set temperature of 21 °C is applied.
Set temperature step down: Starting from the steady state at 21 °C, the set temperature is reduced to 16 °C. Again, the temperature after 4 hours of free cooling and the time required to reach the set temperature is noted.

3. Results

After 4 hours of heating on maximal power, the empty massive room reaches 23.3 °C, while both the furnished room and the room with floor covering have respectively 0.6 and 0.7 K lower temperatures. The furnished room with floor covering achieves a total difference of 1.2 K in comparison to the empty room. The effects for the periodic analysis are similar. After 4 hours of free cooling, the resulting temperature differences towards the empty room are distinctly lower, with a deviation of approximately 0.2 K for furniture or floor covering and a total difference of 0.3 K for the fully equipped massive room. Differences between the massive and the lightweight room are lower than 0.3 K in the heating scenario and almost negligible for the temperature reduction. The detailed temperature changes for all simulations are given in Table 3 and presented in Figure 1 for the massive construction case. Figure 1 also clearly depicts that the impact of the set temperature change upon the room temperature is higher when increasing the set temperature as for the set temperature reduction. Still, it is visible that in all analysed cases the room temperature is distinctly less influenced by the set temperature change if the simulated rooms are equipped with furniture or floor covering.

Table 3. Room temperature and temperature difference between furnished and empty rooms after 4 hours

variant (M / L)	E	F	C	C&F
profile		ΔT (F ↔ E)	ΔT (C ↔ E)	ΔT (C&F ↔ E)
temperature / ΔT after a 4 h step up [in °C]	23.3 / 23.6	22.7 / 22.9	22.5 / 22.8	22.1 / 22.2
		-0.55 / -0.75	-0.72 / -0.83	-1.15 / -1.43
temperature / ΔT after a 4 h step down [in °C]	20.4 / 20.4	20.6 / 20.5	20.6 / 20.6	20.7 / 20.7
		0.15 / 0.15	0.18 / 0.18	0.30 / 0.30

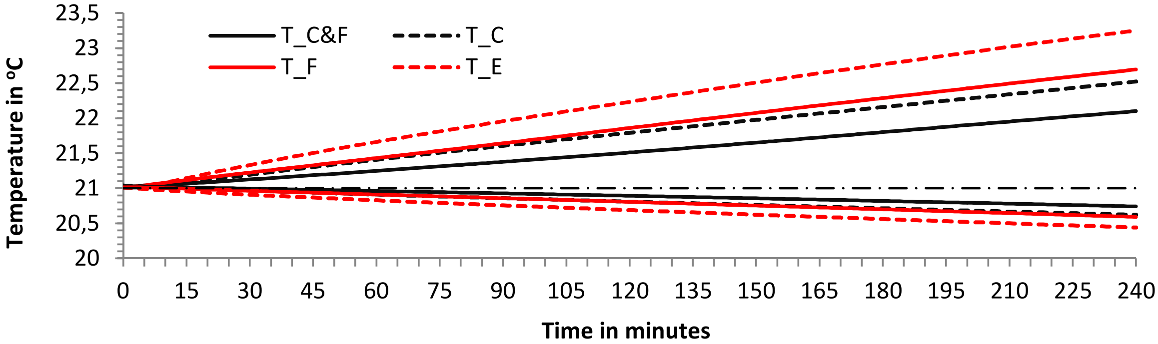

Figure 1. Room temperatures in the four different room setups for the 4 h set temperature step up / step down

When heating the room until the room temperature raises by 5 K, thus to 26 °C, time differences of more than 7 h between empty and fully equipped massive room are detected, therein the floor covering has stronger impact on the required heating time than the installed furniture. Due to the good insulation of the room, the temperature reduction of 5 K requires approximately 81 h for the empty room. The fully equipped room needs approximately 13 h more, and again the floor covering has a higher impact than the furniture. In this analysis differences between massive and lightweight room were distinct, having extensively more damping impact on the consequently slow cool-down process than on the quicker room temperature increase. Also, the effect of furniture compared to the effect floor covering becomes more important for the lightweight room. In the periodic analysis the empty room needed 12 h to cool down to 21 °C, while the fully equipped room required 14 h. The impact of furniture was slightly higher than the impact of floor covering in the periodic analysis. The detailed temporal results of the simulations are given in Table 5.

Table 5. Time it takes to achieve the set temperature and difference between furnished and empty room

variant (M / L)	E	F	C	C&F
		Δt (F ↔ E)	Δt (C ↔ E)	Δt (C&F ↔ E)
required time / Δt for a step up to 26 °C [in h]	11.5 / 7.9	13.8 / 10.2	15.9 / 10.5	18.8 / 13.3
		2.36 / 2.22	4.49 / 2.53	7.31 / 5.35
required time / Δt for a step down to 16 °C [in h]	81.1 / 36.4	86.2 / 43.2	88.7 / 40.5	94.2 / 47.9
		5.03 / 6.87	7.59 / 4.13	13.1 / 11.6

4. Discussion

In general, distinct differences between the thermal behaviour of empty and furnished rooms were found. When performing 4-hour set temperature steps in a well-insulated massive building, the actual temperature increase for the step up (1.1 K for C&F and 2.3 K for E) is distinctly higher than the decrease for the step down (0.3 K for C&F and 0.6 K for E) as compared in Figure 1. Therefore, due to the larger driving temperature difference between room air and furniture, the impact of the thermal mass of furniture is much more significant in the heating scenario.

The effect of floor covering is generally stronger than the effect of furniture. This can be explained by the thermal insulator properties of flooring, which are separating the heating system from the analysed room, while the furniture is just adding thermal mass to the room. In the heating case, the floor covering decouples the heating system from the room and thus from most of the rooms' thermal mass. In turn, for the cooling case the most charged thermal mass (the floor) is separated from the rest of the room. However, the insulating effect of flooring for the cool-down scenario is only visible for severe temperature reductions in the time range of many days. Short-time temperature steps only show the effect in the scenario with increasing temperature. Further, it is found that the effect of the set temperature increase does not change if these steps are repeated periodically; that at least as long as the room temperature can stabilize before the next periodic heating phase occurs. Still, furnishing and floor covers within the room changed cool-down times by up to 2 hours in the periodic case.

The difference between lightweight and massive buildings is very small for short-time set temperature steps. However, for long-lasting and severe temperature changes the impact of the rooms' materials becomes clear. Also, for lightweight buildings the effect of furnishing plays a stronger role, since it contributes a larger share of the total thermal mass.

5. Conclusion

It has been shown that both the furniture and the floor covering within a room have a distinct impact upon the simulated room temperatures under dynamic set temperature conditions. The magnitude of both the detected time lag and temperature difference changes with the choice of construction, furnishing, and flooring materials. However, the fact that these influences are clearly detectable and substantial, underlines the importance of considering more than an empty room in thermal simulations. Still, it was found, that for short periods with lower set temperatures the effect is less significant. Since in the past buildings were usually simulated under steady state conditions or only considering short temperature reductions e.g. night temperature set-back, the effects of furnishing and floor covering were indeed not having a great impact on the thermal building performance. However, if there is an intention to use the buildings' thermal mass as energy storage by dynamically heating the building, the detected effects are considerable. After just 4 hours with increased set temperature, the empty massive room was 1.2 K warmer than the same modelled room with flooring and furniture inside. If such simulations are used to control the dynamic thermal mass activation, discrepancies in that range can strongly limit the system's potential, especially when taking into account that the comfort range of inhabitants will only allow temperature deviations of a few degrees. In further analysis we will simulate the control of differently furnished rooms with a thermal mass activation algorithm to understand how the found temperature off-set impacts the demand-shifting potential of buildings. Finally, we would strongly suggest considering that depending on the question being analysed with a given thermal building model, it might be beneficial to extend the pure representation of the building by interior elements like furnishing and floor covering.

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